hybridGEOTABS project

– MPC for controlling the power of the ground by integration

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GEOTABS is an acronym for a GEOthermal heat pump combined with a Thermally Activated Building System (TABS). GEOTABS combines the use of geothermal energy, which is an almost limitless and ubiquitous energy source, with radiant heating and cooling systems, which can provide very comfortable conditioning of the indoor space. GEOTABShybrid refers to the integration of GEOTABS with secondary heating and cooling systems and other renewable and residual energy sources (R2ES), offering a huge potential to meet heating and cooling needs in office buildings, elderly care homes, schools and multi-family buildings throughout Europe in a sustainable way. Through the use of Model Predictive Control (MPC), a new control-integrated building design procedure and a readily applicable commercial system solution in GEOTABShybrid, the overall efficiency of heating and cooling will be significantly improved in comparison to current best practice GEOTABS systems and its competitiveness will be strengthened.

The present paper is the first of a series that first introduces the hybridGEOTABS project and then specifically focuses on the control-related aspects of the hybridGEOTABS solution, the MPC, providing some interesting insights of its potential development.

Keywords: hybridGEOTABS; geothermal heat pump; TABS; Model Predictive Control, integrated solution

GEOTABS benefits & challenges

GEOTABS are applied in low temperature heating and high temperature cooling of buildings. TABS is a radiant system, beneficial in terms of thermal comfort and energy efficiency. Its high thermal inertia allows load buffering and peak load shaving. When combined with a heat pump, it allows to make very efficient use of low grade R2ES (renewable and residual energy sources) (**Figure 1**). Therefore, GEOTABS represents an eco-innovative technology that allows to substantially decrease energy use and greenhouse gas (GHG) emissions from buildings while improving indoor environmental quality. The GEOTABS project [1] was a frontrunner in improving system design and control of GEO-HP-TABS in office buildings by using monitoring, comfort surveys and simulation data. The resulting design guidelines were included in REHVA Guidebook 20 "Advanced system design and operation of GEOTABS buildings [2].

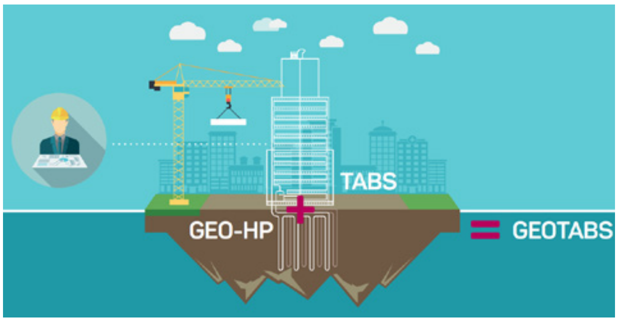

Figure 1. The GEOTABS concept. Image credits: hybridGEOTABS project (www.hybridgeotabs.eu)

Nonetheless, a number of bottlenecks currently prevent a real breakthrough of the GEOTABS concept in a broad range of building types. Current GEOTABS solutions are perceived too investment-expensive and they are often not operating at their full potential. Because of their high thermal inertia, TABS require flexible complementary heat emission systems to swiftly react to variations in heating or cooling setpoint, ensuring thermal comfort and efficient operation. On the production side, investments can be more competitive when providing a hybrid supply, and heat pump operation can be more efficient. The GEOTABS system is thus an inherently hybrid system when we want to use it in a broad range of building types, including those buildings with highly variable and often unpredictable heating and cooling loads. Challenges however need to be tackled to integrate the primary and secondary systems. A first challenge is the lack of design guidelines

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hybrid GEOTABS

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– Model Predictive Control and Innovative System Integration of GEOTABS in Hybrid Low Grade Thermal Energy Systems

hybridGEOTABS is a four-year project started in 2016 by an active team of SMEs, manufacturers and research institutes. The project, led by the University of Gent, is a Research and Innovation Action funded under the EU's Horizon 2020 programme.

The goal of hybridGEOTABS is to optimise the predesign and operation of a hybrid combination of geo-thermal heat-pumps (GEO-HP) and thermally activate building systems (TABS), alongside secondary heating & cooling systems, including automated Model Predictive Control (MPC) solutions.

To know more about the project visit www.hybridgeotabs.eu and contact hybridgeotabs@ugent.be

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on the sizing of the hybrid GEOTABS system to allow a proper tuning between heating and cooling originating from the GEOTABS and that provided by the complementary system. Today case-by-case dynamic simulations are required in design phase, resulting in excessive engineering costs. Secondly, the resulting oversizing of the heat pump and borefield leads to higher investment costs. Thirdly, for the concept to work at its most efficient point, all components need to be engineered as a package, which is rarely the case since they are developed by different companies, leading to higher investments and lower efficiencies. Fourthly, traditional Rule-Based Control strategies are not able to harvest the full potential of the system and result in high commissioning costs and higher operational costs. Finally, previous studies have shown potential benefits of the system in terms of thermal comfort, health and productivity, yet those have not been fully validated yet.

hybridGEOTABS solution & project

The hybridGEOTABS project [3] brought together a transdisciplinary team of SME's, large industry and research institutes, experienced in research and application of design and control systems in the combined building and energy world (**Figure 2**). Their aim is to take away the bottlenecks to allow a wide implementation of the hybridGEOTABS concept. The overall solution consists of an optimal integration of GEOTABS with secondary systems and a white box approach for model predictive control (MPC) of this integrated system. The main objectives of the project are to develop, demonstrate and validate the hybridGEOTABS system.

hybridGEOTABS key objectives are:

1. The hybridGEOTABS system will be developed and supported by a new holistic control-integrated design procedure, with the overall efficiency for heating and cooling improved by 25 % as compared to current best practice GEOTABS. This coherent strategy will allow to provide feedback about the HVAC systems in the feasibility study/pre-design stage of the design process, as well as a significant reduction of engineering costs for hybridGEOTABS buildings.
2. A method of choosing the appropriate components for hybridGEOTABS, e.g. bore holes, heat pumps, TABS, control, and secondary supply and emission systems, is developed in order to achieve optimal performance of the integrated system. These components are also optimised and developed for use in hybridGEOTABS, and an energy dashboard is developed to involve and inform building operators and users. As an alternative for the use of TABS in building retrofit, the potential of using radiant ceiling panels with integrated Phase Change Materials is being investigated.
3. A suitable control system with the MPC as the high-level controller and state-of-the-art low-level controllers is developed. A semi-automated MPC toolchain for the development of this controller is developed. The MPC is based on a white-box model and will be adaptive and robust. Therefore, it will reduce the implementation cost of MPC to competitive levels, by reducing both design and commissioning costs, and maximise building performance. The white-box

Figure 2. The hybridGEOTABS consortium includes four universities, four SMEs, one professional association, one SME cluster and two large companies.

MPC also allows for an immediate start-up of the control with the start-up of the building (with no need for training data).
4. A people-planet-profit validation of the hybridGEOTABS approach on high-visibility demonstration and case-study buildings. The evaluated performance indicators include energy and environmental indicators, indoor environmental quality indicators (thermal comfort, acoustics, lighting…, and importantly, also health and productivity are evaluated), financial costs and other performance indicators such as smart grid readiness.
5. The groundwork for the establishment of a trade body to promote the concept and help to establish the best practices according to the project will be laid down.
6. A detailed business plan will be developed to promote the product and maximize the project impact.

hybridGEOTABS demonstration buildings

The hybridGEOTABS implementation, demonstration and validation takes place in 3 demonstration buildings:

- Ter Potterie elderly care home in Bruges (Belgium) (**Figure 3A**),
- Solarwind office building in Windhof (Luxembourg) (**Figure 3B**),
- the elementary school of Libeznice (Czech Republic) (**Figure 3C**).

In these buildings, the newly developed control strategies are implemented and validated and the overall building performance (in terms of energy, environment, costs, comfort, health and productivity) is evaluated via on-site measurements and building data. These three demonstration buildings, together with two extra case-study buildings, Infrax office building in Dilbeek (Belgium) (**Figure 3D**) and Haus M multi-family building in Zürich (Switzerland) (**Figure 3E**), populate a virtual test bed consisting of emulator models of these buildings, that are used in the development, demonstration and validation of the concept.

Why Model Predictive Control?

MPC is a control methodology that can be used to control thermal systems (heating, cooling and ventilation) in buildings and which is an alternative for Rule-Based Control (RBC). The principle of MPC is fundamentally different from RBC since MPC uses a mathematical optimization problem at its core instead of a set of fixed control rules. The optimization problem minimizes a cost function, e.g. the energy use of the building, by choosing the control variables, e.g. the supply water temperature of floor heating, optimally. Furthermore, constraints can be enforced in the optimization problem, such as a minimum and maximum zone temperature. This way thermal comfort is guaranteed. Finally, MPC includes an internal forecast of the system state (temperatures) such that it can anticipate the influence of future disturbances (e.g. outdoor temperature and occupancy).

Figure 3. hybridGEOTABS demo buildings: A) TerPotterie, Bruges B) Solarwind, Windhof C) Libeznice primary school, D) Infrax building, Dilbeek E) Haus M, Zurich. Image credits: hybridGEOTABS project (www.hybridgeotabs.eu)

To be able to implement an MPC, the controller has to know how 'the system' behaves. I.e. the controller has to know how a change in control variables affects the constraints and the objective function. This information is contained by a 'controller model', which is a mathematical representation of the controlled system. **Figure 4** presents a schematic illustration of MPC.

An analogy can be made with a Formula 1 car (see **Figure 5**). The pilot is then the optimal controller. His cost function (objective) is to complete the track as quickly as possible. Control variables are the steering wheel, the throttle and the brakes. Constraints are the edges of the circuit and the maximum traction of the tires. The pilot knows how the car reacts to his 'control signals' and is thus able to complete the track quickly. The better its controller model (driving skills), the better the results (lap times) will be.

In the case of a building it is not feasible to have a person operating the building full time. Computers can however take over this task. Computers can also use machine learning to learn the behavior of the building, similar to how a Formula 1 pilot learns the behavior of his car. However, just like a pilot, a computer requires a lot of training to achieve these skills. In the case of a complex building this may take multiple years of training data, which is not a practically workable solution. This is an important disadvantage of such a data driven approach. These data driven approaches are often classified as 'black-box' approaches since the controller knows nothing about the controlled system. White-box and grey-box approaches are an alternative to black-box by including more physical knowledge about the system.

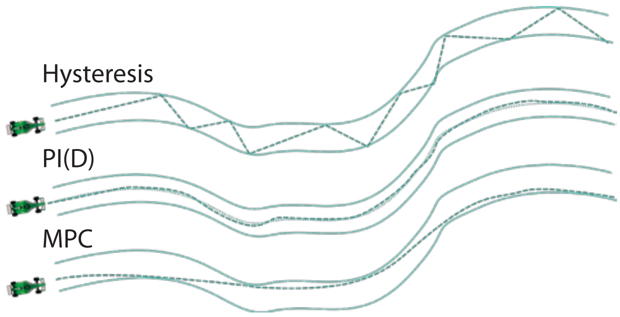

Figure 5. Formula 1 car analogy: Rule-Based Control (Hysteresis) vs. proportional control (PI(D)) vs. Model Predictive Control (MPC).

The white-box approach to MPC

White-box is the other extreme of the controller model spectrum, where knowledge about the physical system is included as much as possible. This knowledge is used as a substitute for measurement data. We do this by describing the system mathematically, using equations that express conservation of energy, COP or efficiency curves and the thermal inertia of the building. This approach allows developing controller models in a systematic way using building schematics and technical data, even before the building has been constructed. A disadvantage of this approach is that the computation time for the optimization of these detailed models rises strongly. The development of these models also requires some expertise in optimization and building energy simulation. Every building is different and therefore the controller model development is a recurring cost, which should be limited.

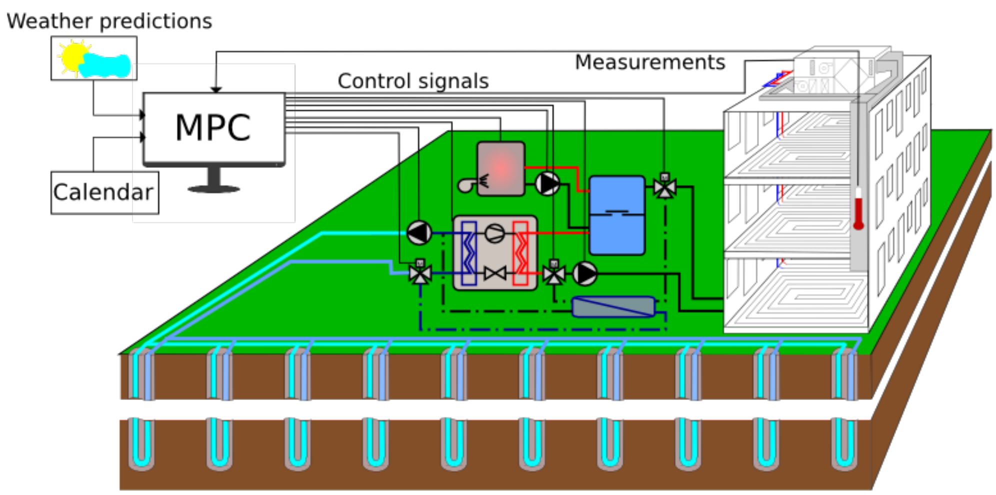

Figure 4. Schematic illustration of MPC in the larger system.

Scientific research within the hybridGEOTABS project and at the Thermal Systems Simulation (The SySi's) research group of the KU Leuven has however developed a solution for these problems. They developed a methodology that splits the controller model development work in three parts, using the modelling language Modelica.

1. PART 1. The first part is IDEAS, an open-source Modelica library of component models [4]. The library contains mathematical models for heat pumps, valves, windows, walls, solar shading, etc. These models are parameterized using easily interpretable parameters such as type numbers, wall surface areas and U-values. The models have been developed specifically for optimization purposes, by modelling experts.
2. PART 2. As the second part, users such as engineering firms and control companies can use this library by configuring components and by connecting them using connections that correspond to physical reality, e.g. using pipes. Similarly, window models and wall models can be connected to a room model. This leads to a structured mathematical description of the building, including its HVAC equipment and building envelope.
3. PART 3. In a third step, a computer program translates this structured description into an optimization code. Since the model library and the program are tailored to each other, very efficient optimization code can be generated such that problems related to the optimization problem computation time are largely resolved. Furthermore, users require a lot less expertise since the optimization problem complexity is encapsulated in the component model mathematical descriptions.

MPC current and future potential

Why is this important? MPC has multiple advantages compared to RBC, of which energy savings are the easiest to quantify. Research studies typically report energy savings of 15 to 30 % in practical demonstration cases, but some studies have reported energy savings of more than 50 % [5-9]. Since the ventilation, heating and cooling of buildings is responsible for about 15 % of the world wide final energy use [10], MPC can lead to significant energy and cost savings. These savings are obtained by operating the systems more efficiently and by better anticipating external factors such as weather influences. The thermal mass of the building can for instance be used to store 'free' energy of the sun on sunny days, due to which the heating requirements are reduced.

Furthermore, MPCs are able to use the available systems to their full potential. E.g. excess heat in one side of the building can be actively rerouted to other zones through floor heating or concrete core activation. In the future such energy exchanges may even occur at a larger scale between buildings, when using thermal networks. Other advantages are the increased thermal comfort and reduced wear on components that operate in part-load or by avoiding cyclic behavior.

There are additional advantages that have not been shown systematically but for which we see a large potential. The commissioning cost of a building could be reduced significantly compared to RBC. MPCs are more flexible and are better able to cope with changing set points and malfunctioning equipment than RBC. MPC supports multiple cost functions such that the energy cost (EUR) could be minimized instead of the energy use (kWh). This is particularly interesting when a day/night tariff or even time-dependent electrical energy pricings are available. MPC is hence a technology that is compatible with the smart grids of the future, and also with demand response. Companies with a heart for the environment can also modify the cost function such that locally generated renewable energy sources are put to use as much as possible. This could be a very useful tool for policies during the transition to a CO2-neutral society. Policy goals can be translated into a gradual increase in the share of renewable energy that should be used. MPC can then automatically control hybrid systems (such as hybrid heat pumps) such that this gradual increase is achieved. Furthermore, the mathematical models can also be used for other purposes such as fault detection and diagnosis or simply for predicting the indoor air temperature during the coming days. This is possible since an MPC internally predicts the future behavior of the building to implement the optimization, which thus takes into account the impact of the current control actions on the future behavior of the building.

hybridGEOTABS project for boosting MPC development

The hybridGEOTABS project incorporates an overall and integrated system approach, it considers all stages of the building process (from predesign to operational stage) and validates the concept from many perspectives via a people-planet-profit validation. The project will play a pivotal role particularly for the future development and market uptake of MPC. Indeed, MPC is ready for the early adopters, but for a large-scale deployment based on the white-box approach some issues have to be resolved first. The library of component models has to be extended and the user-friendliness of the toolchain can be improved. Furthermore, the technology should be demonstrated in practice. These aspects are planned for the coming months within the scope of the hybridGEOTABS project, where in three demonstration buildings the hybridGEOTABS concept with MPC will be implemented, demonstrated and validated. ■

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